Improving the sensitivity of Higgs boson searches in the “golden channel”

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arXiv:1108.2274: In collaboration with Jamie Gainer, Kunal Kumar and Ian Low

Overview

- Objective
- Review of the "Golden Channel"
- Statistical Analysis
- Detector Effects
- Results
- Conclusions/Future Work

Objective

- Set up a matrix element method analysis to examine the Higgs boson signal in the $ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ channel
- Compare how much improvement in significance is gained by using the full kinematic distribution of the decay products versus using only the total invariant mass
- Examine how the two cases compare when setting exclusion limits
- Conduct analysis for Higgs mass $(175 - 350$ GeV) for a 7 TeV LHC
- Examine other signals with different spins and extract them from backgrounds

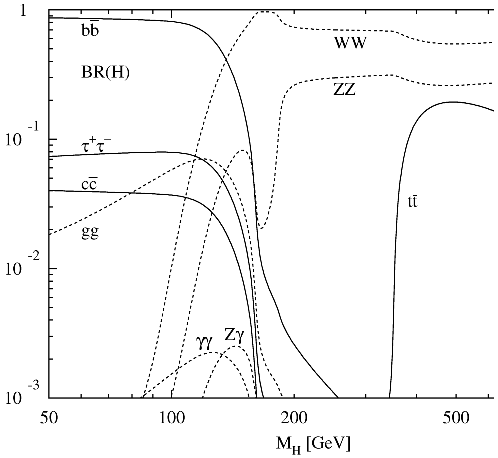
Golden Channel

- Golden Channel: $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$
- Has been examined using the Matrix Element Method in earlier studies in the context of signal discrimination for 10 and 14 TeV

  De Rujula, Lykken et al: arXiv:1001.5300, Gao, Gritsan, Melnikov et al: arXiv:1001.3396
- Very "clean" channel due to high precision with which e and μ are measured and is fully reconstructable
- Typically thought to be an "easy" mode of Higgs discovery...however...

Golden Channel

- Suffers from small cross sections due to branching fractions of $H \to ZZ^* \sim .3$ and *Zs* to leptons $\sim .0335$

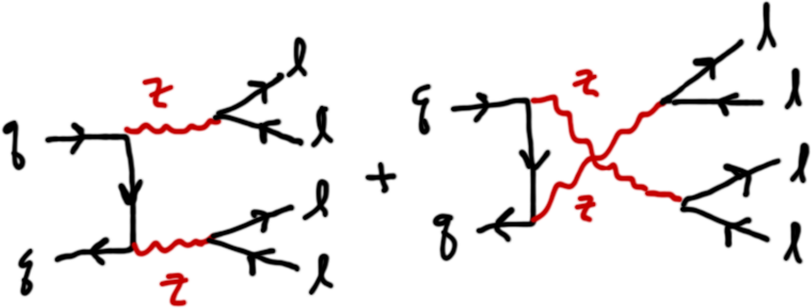


A. Djouadi, J. Kalinowski, M. Spira

hep-ph/9704448v1

Golden Channel: Background

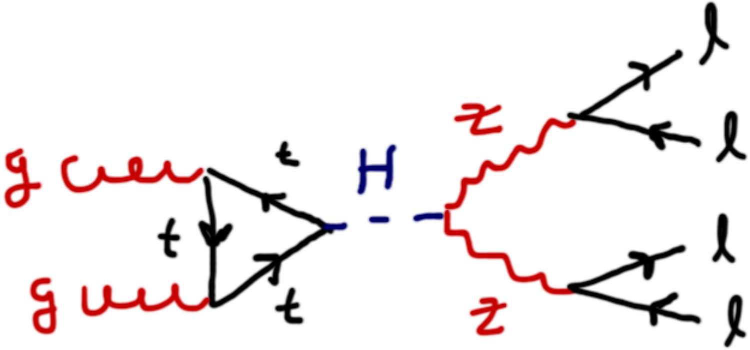
- $q\bar{q} \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ is the dominant irreducible background for $175 < mh < 350$
- We include the 3 separate channels $ee\mu\mu$, 4μ and $4e$ at LO



- In the high energy limit the amplitudes for two transverse Z bosons $\mathcal{A}_{\pm\mp}$ dominate

Golden Channel: Signal

- The dominant production mechanism is $gg \to H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ through a top quark loop
- We consider the LO contribution only which is given by



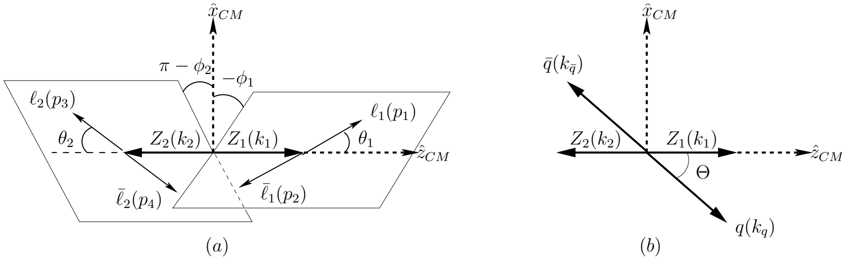
- In the high energy limit the amplitudes for two longitudinal Z bosons $\mathcal{A}_{00}$ dominate

Golden Channel: Observables

- In the $ee\mu\mu$ channel there is no ambiguity in defining the lepton angles since the final states are distinguishable
- For the 4μ and 4e channels we use the reconstructed Z masses to distinguish the pairs
- In the massless lepton approximation there are 12 observables per event (pT, η, Φ for each lepton)
- Using momentum conservation and the azimuthal symmetry of the detector we can reduce these to the set $x_i \equiv (x_1, x_2, M_1, M_2, \hat{s}, \Theta, \theta_1, \phi_1, \theta_2, \phi_2)$

Golden Channel: Observables

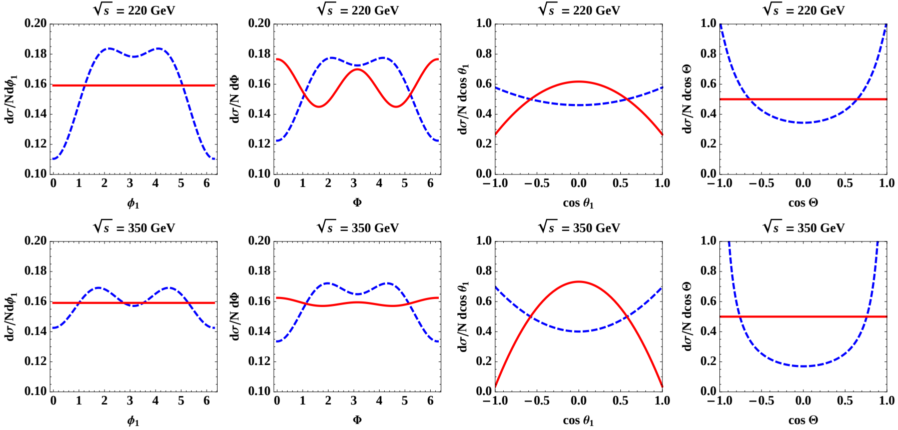
- The angle Θ is defined in the ZZ rest frame



- The angles θ_1, ϕ_1 and θ_2, ϕ_2 are defined in the rest frame of the Z which decays to electrons and muons respectively

Golden Channel: Distributions

- The angular distributions can add to our discriminating power



Statistical Analysis

- The Matrix Element Method: use of likelihood methods where normalized differential cross sections are used as pdf in the likelihood
- We define our significance as

$$\mathcal{S} = \sqrt{2ln\mathcal{Q}}$$

where $\mathcal{Q}$ is the likelihood ratio given by

$$\mathcal{Q} = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b}$$

- Shown to be a robust test statistic in the low statistics regime

LEP Working Group: arXiv:9903282, V. Bartsch, G. Quast:CMS NOTE 2005/004

Statistical Analysis: Likelihood Function

- For our likelihood we use an Extended Maximum Likelihood (EML) function

$$\mathcal{L}_{s+b}(\mu, f, m_h) = \frac{e^{-\mu}\mu^N}{N!}\prod_{i=1}^{N}[fP_s(m_h; x_i) + (1-f)P_b(x_i)]$$

- P_s and P_b are the signal and background pdfs (normalized differential cross sections) computed in helicity amplitudes:

$$P_s(m_h; \boldsymbol{x}) = \frac{1}{\epsilon_s\sigma_s(m_h)}\left(\frac{f_g(x_1)f_g(x_2)}{s}\right)\frac{d\widehat{\sigma}_h(m_h, \hat{s}, m_1, m_2, \Omega)}{dY\, d\hat{s}\, dm_1^2\, dm_2^2\, d\Omega}$$

$$P_b(\boldsymbol{x}) = \frac{1}{\epsilon_b\sigma_{q\bar{q}}}\left(\left(\frac{f_q(x_1)f_{\bar{q}}(x_2)}{s}\right)\frac{d\widehat{\sigma}_{q\bar{q}}(\hat{s}, m_1, m_2, \Omega)}{dY\, d\hat{s}\, dm_1^2\, dm_2^2\, d\Omega} + \left(\frac{f_{\bar{q}}(x_1)f_q(x_2)}{s}\right)\frac{d\widehat{\sigma}_{q\bar{q}}(\hat{s}, m_1, m_2, \Omega')}{dY\, d\hat{s}\, dm_1^2\, dm_2^2\, d\Omega'}\right)$$

where $\Omega' \equiv (\pi - \Theta, \theta_1, \theta_2, \phi_1 + \pi, \phi_2 + \pi)$ for initial quark in the $-z$ direction and we have switched x_1 and x_2

Analysis: Expected Significance

- To obtain the expected significance we construct the PDF for $\mathcal{S}$ by conducting a large number of psuedo experiments and obtaining $\mathcal{S}$ for each one
- To remove the dependance of $\mathcal{S}$ on the undetermined parameters we maximize the EML function prior to the construction of the likelihood ratio
- So we have for the likelihood ratio

$$\mathcal{Q} = \frac{\mathcal{L}_{s+b}(\hat{N}t, \hat{f}s, \hat{m}h; x_i)}{\mathcal{L}_b(\hat{N}_t; x_i)}$$

where $\hat{N}t, \hat{f}s, \hat{m}h$ are the values which maximize the EML function for a given psuedo experiment

Statistical Analysis: Exclusion Limit

- We determine the exclusion limit, in the absence of a signal, by setting an upper limit on the signal fractional yield, $0 < f = \frac{\mu_s}{\mu_s + \mu_b} < 1$
- For a particular choice of Higgs mass $\hat{m}_h$, we define a pdf by considering the likelihood $\mathcal{L}_{s+b}$ as a function of f

$$p(f) = \frac{\mathcal{L}_{s+b}(N, f, \hat{m}_h)}{\int_0^1 \mathcal{L}_{s+b}(N, \bar{f}, \hat{m}_h)\, d\bar{f}}$$

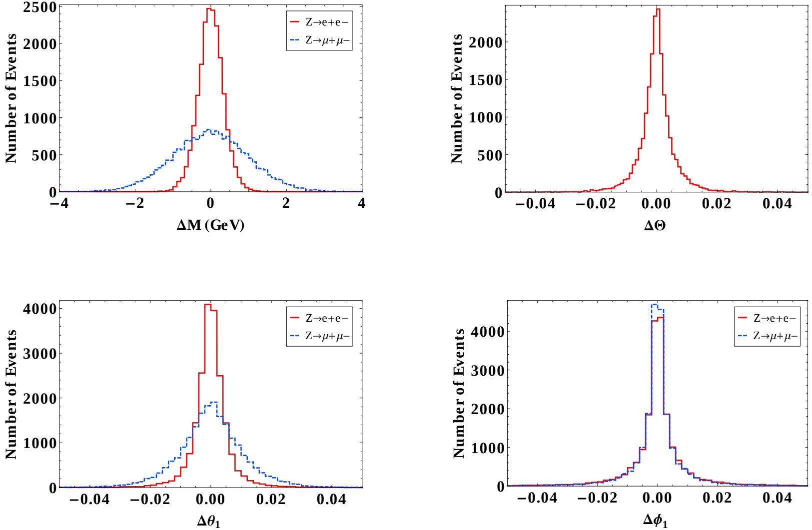
  The 95% confidence level limit on f for a given set of data is given by α as follows:

$$\int_0^{\alpha} p(f)\, df = 0.95$$

- We then translate α into a 95% confidence level upper limit on the Higgs production cross section by unfolding with the detector acceptances and efficiencies

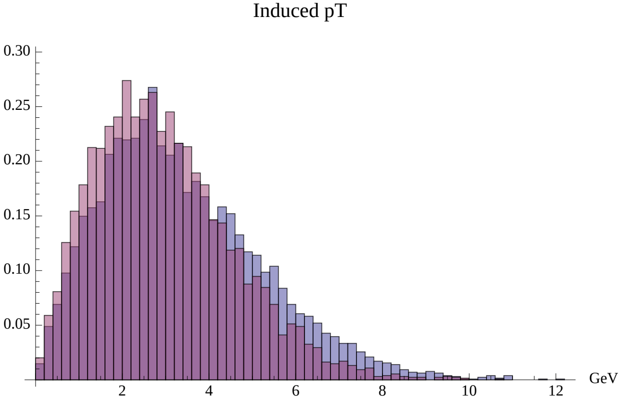
Detector Effects: Smearing

- We apply separate smearing to energy of the electrons and p_T of the muons according to CMS TDR



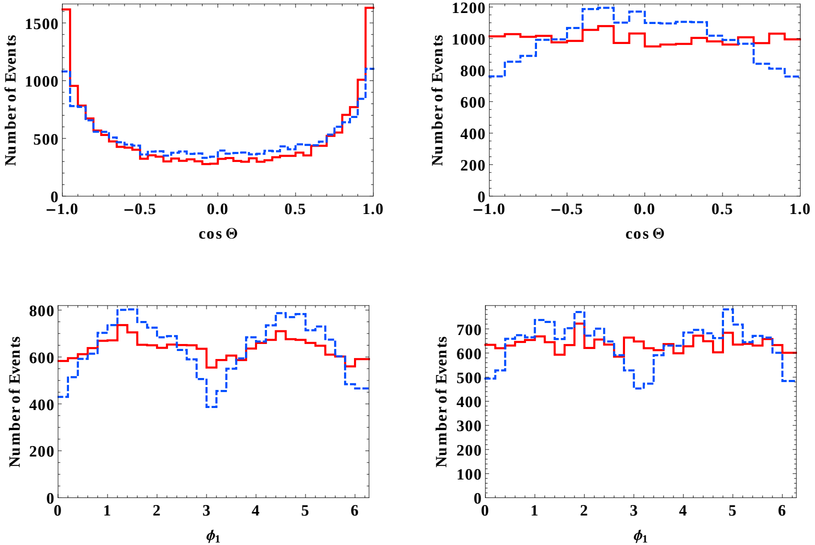
Detector Effects: pT dependence

- For simplicity we consider only the 0-jet bin and since we are considering only LO assume events have no intrinsic *pT*
- Cuts and detector smearing can shape distributions and introduce a *pT* dependence even when only considering the LO process
- To find the ZZ CM frame, must ensure *pT* is be properly boosted away on an event by event basis



Detector Effects: Cuts

- We require: pT > 10 GeV, η < 2.5, and $150 < \hat{s} < 450$



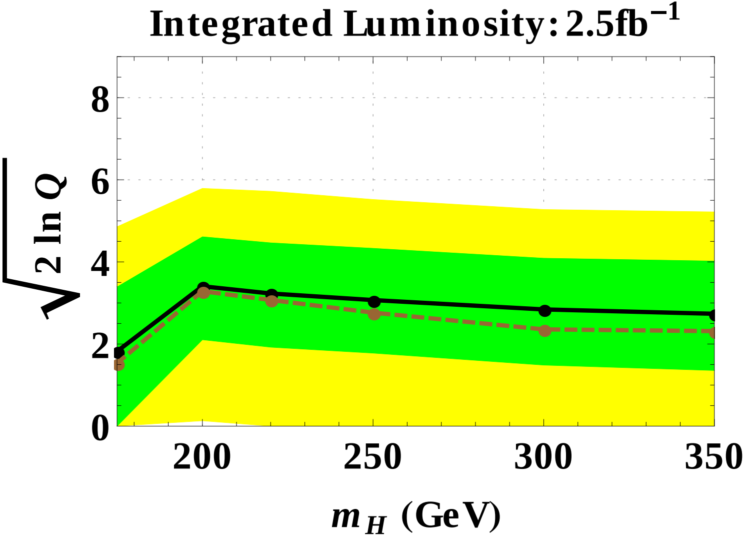
Efficiencies and Yields

- After detector effects and cuts we obtain the following efficiencies and yields for the $2e2\mu$ channel at $2.5fb^{-1}$

	m_h(GeV)	σ(fb)	ϵ	$\langle N \rangle$
Signal	175	0.218	0.512	0.279
	200	1.26	0.594	1.87
	220	1.16	0.625	1.81
	250	0.958	0.654	1.57
	300	0.714	0.701	1.25
	350	0.600	0.708	1.06
Background	-	8.78	0.519	11.4

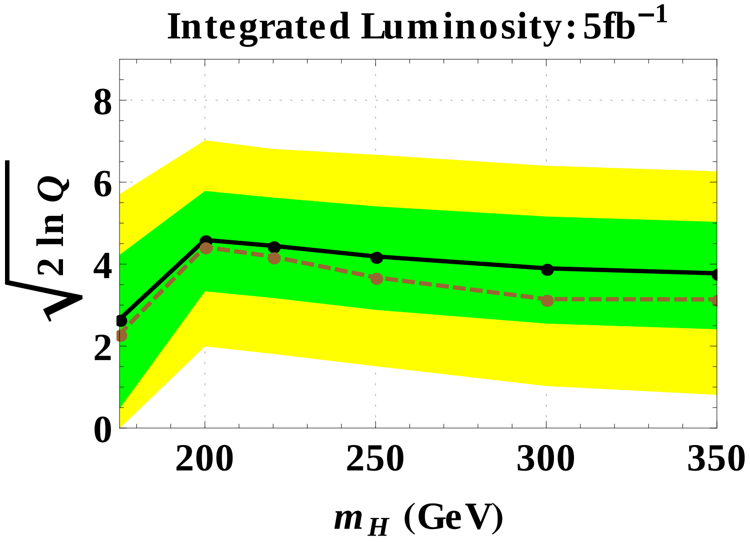
- The efficiencies for $4e$ and 4μ are the same as for $2e2\mu$ while the yields (cross sections) are half as large
- It is these cross sections $\times$ efficiencies which we use to normalize our pdfs in the likelihood function

Results: Expected Significance



arXiv:1108.2274

Results: Expected Significance



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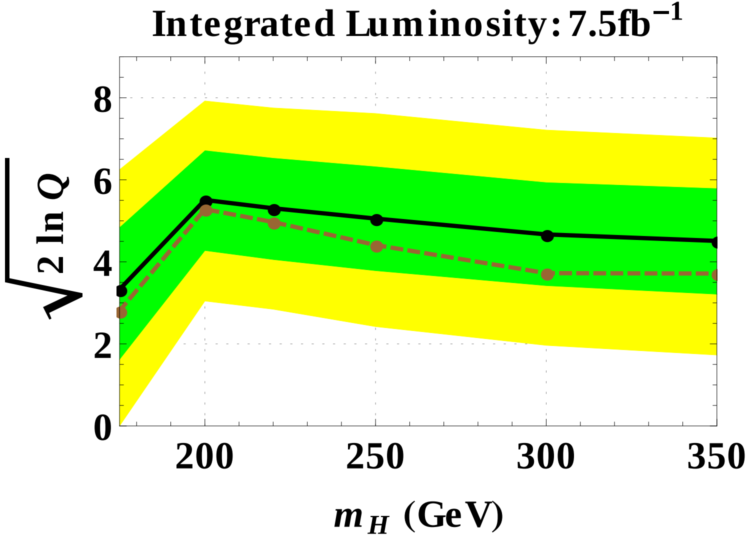
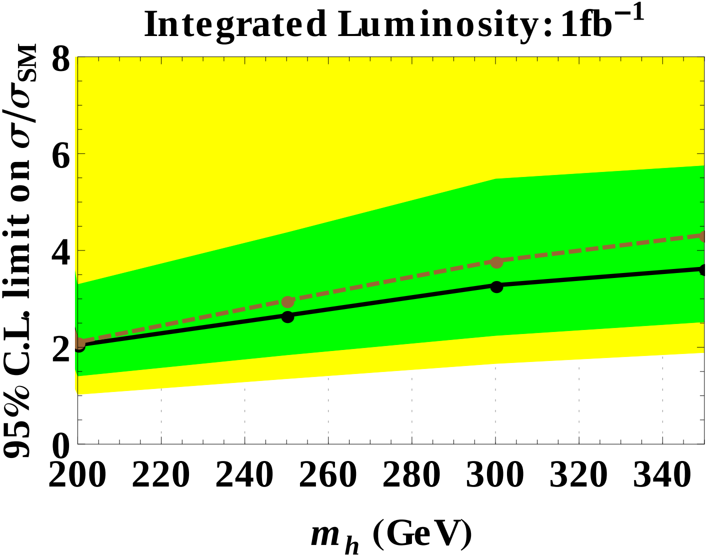


Results: Exclusion Limits



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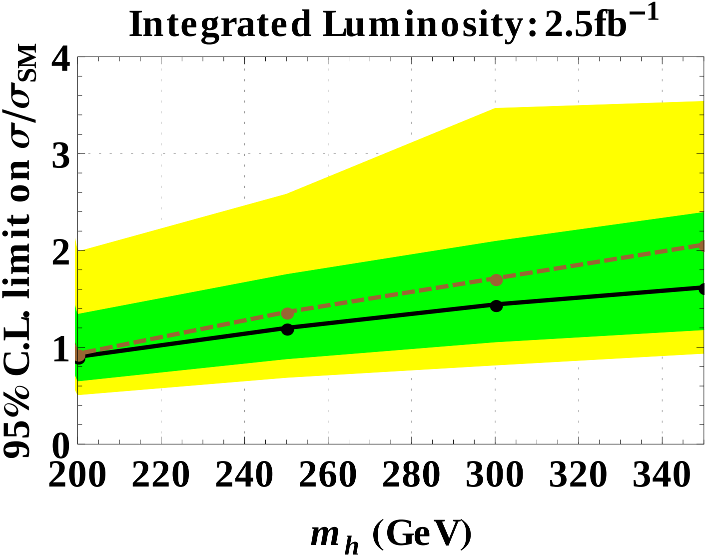

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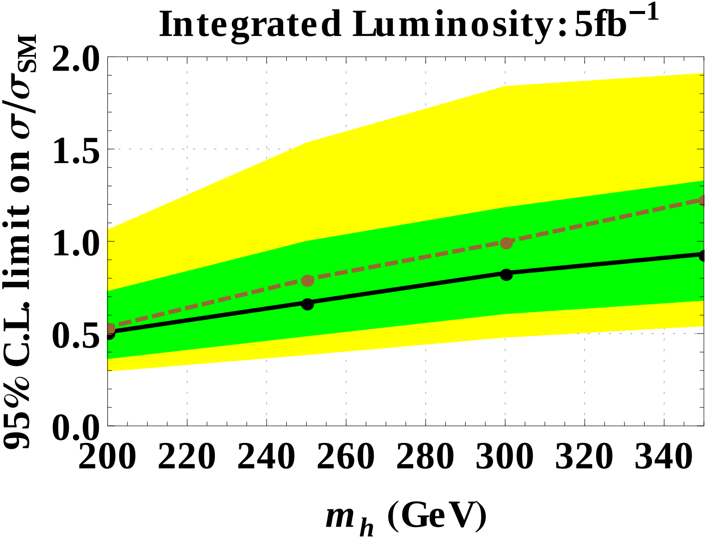

Conclusions/Ongoing and Future Work

- We have analyzed the Higgs “Golden Channel” at a 7TeV LHC using a Matrix Element Method analysis
- We have compared how the MEM performs when one uses the full kinematic information of the event in addition to the total invariant mass and find improvements on the order of $10 - 20\%$ depending on the Higgs mass
- Implement analysis for other resonances including CP odd/even spin 1 and 2 which decay to ZZ^*
- Consider other fully reconstructable processes and perform a similar analysis